

# LATEST PLEISTOCENE AND HOLOCENE VEGETATION AND ENVIRONMENTAL HISTORY OF THE WESTERN PLAINS OF VICTORIA, AUSTRALIA

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Major pollen taxa from 11 records constructed from the basaltic Western Plains of Victoria are examined to provide a regional picture of vegetation and environmental change through the latest Pleistocene and Holocene (i.e. the last 20,000 years). Analogue matching of recent and fossil pollen spectra is employed to determine the degree to which past vegetation is related to any communities present today and to make quantitative estimates of past rainfall. The plains were virtually devoid of trees during conditions of the Last Glacial Maximum but rainfall was lowest between about 14,000 and 12,000 years ago within the succeeding late glacial period. Woodland expansion is evident from about 12,000 years ago. There are marked differences between the western, northern and eastern parts of the plains in woodland composition and timing of development within the early Holocene, possibly due to an atmospheric circulation pattern different to that of today. Around 8000-7000 years ago, the vegetation cover present at the time of European arrival was established and, despite evidence for substantial changes in water levels within Western Plains lakes, the vegetation has remained resilient to apparent significant climate change. The pollen data reflect the major impact that recent land use changes have had on the landscape.

*Key words:* Late Quaternary, crater lakes, volcanic plains, quantitative climate reconstruction, regional vegetation history, Victoria

THE BASALTIC Western Plains of Victoria have long held a fascination for palaeoecologists. The presence of small enclosed lakes provides one of the few opportunities in Australia to produce records that are continuous and free of the many complications that plague interpretations from sub-optimal sites of investigation such as riverine swamps and shallow saline lakes, so characteristic of the Australian environment. The first pollen records from the area were produced by Yezdani (1970). Since that time, the area has been revisited a number of times for purposes such as testing and refining initial interpretations (Dodson 1974), temporally extending the existing record (D'Costa et al. 1989; Dodson 1979; Edncy et al. 1990; Harle et al. 1999; Wagstaff et al. 2001; Kershaw et al. 2004), dating times of volcanic eruption (Head et al. 1991; Sherwood et al. 2004) and examination of impacts of Aboriginal and European people on the landscape (Head 1989; Dodson et al. 1994). Recently, there has been a focus

on the production of high resolution records in order to examine sub-millennial changes in climate, and their relationships to vegetation dynamics and fire regimes (Mooney 1997; John Dodson pers. comm.; Rochelle Johnston pers. comm.; Penny & Tibby unpublished data; Chris White pers. comm.).

This paper attempts a regional reconstruction of vegetation for the latest Pleistocene (c 18,000 to 10,000 radiocarbon years BP) and the Holocene period (the last 10,000 radiocarbon years or the present interglacial) by bringing together available pollen records, some of which have not previously been published. The latest Pleistocene to early Holocene marks the approximate time when the majority of sites began to accumulate sediments continuously or to preserve pollen. Results from 11 sites are presented, and nowhere else in Australia is there such a concentration within an equivalent area.

There are several reasons why a regional synthesis is of value. In the first place, individual



scrub, and the shallow water maars of Lake Wangoom and Lake Terang have been drained. These volcanic lakes and swamps cover a mean annual rainfall range of about 690 to 810 mm per annum, with a winter maximum, but due to the low altitude of the sites, there is little variation between them in mean annual

temperature (13.0°C to 13.8°C). Although rainfall variation is small, it is within a critical range with regards to salt accumulation. The lakes range from fresh to hyper-saline but there is no direct correlation with rainfall as other factors, including ground water influence, basin size and depth and the propensity of

Table 1. Site location and selected attributes

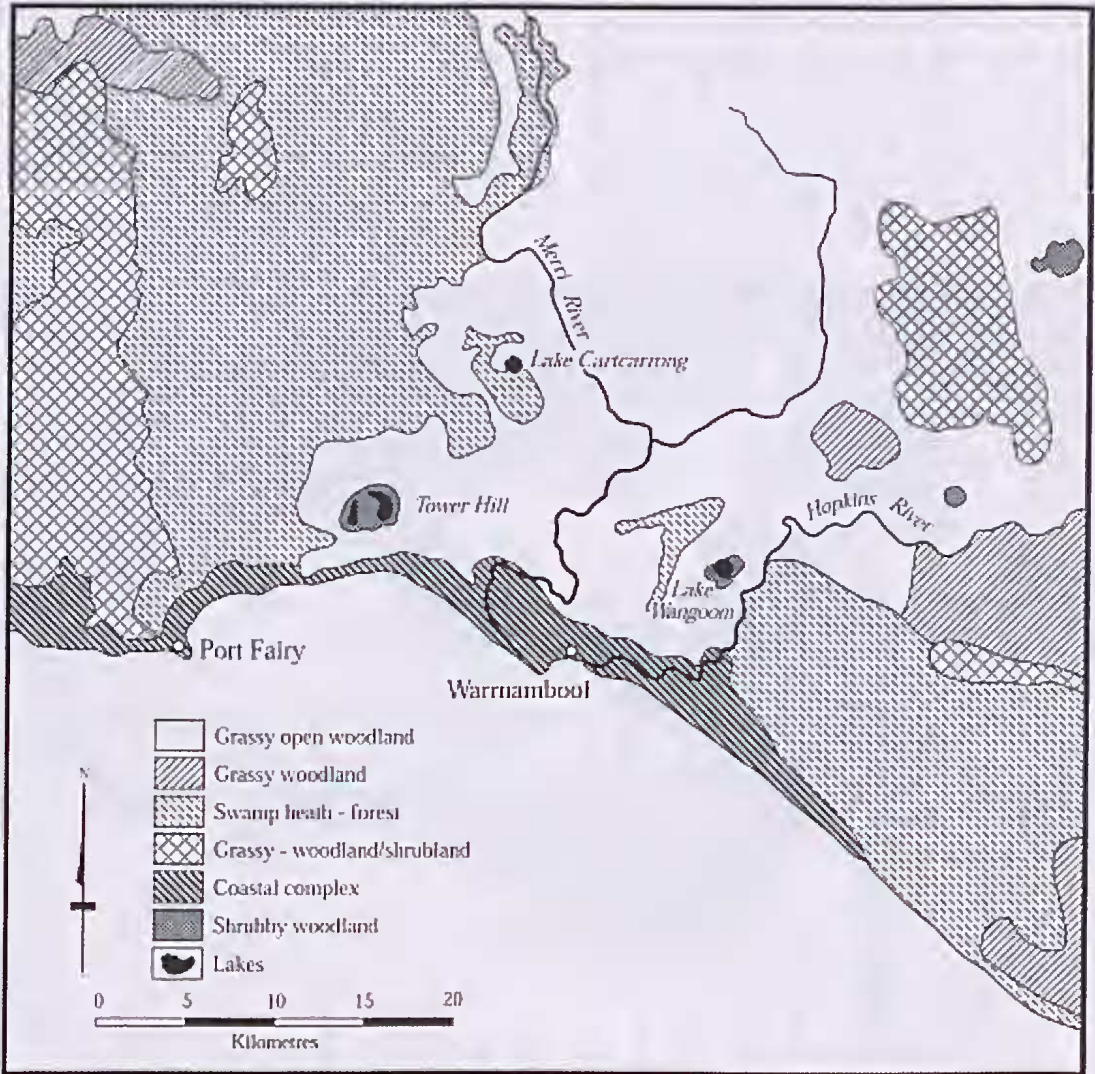
Site	Lat. (S)	Long. (E)	Alt.(m)	Rainfall	Sources of raw pollen data
Tower Hill NW Crater	38° 19'	142° 22'	20	721	D'Costa et al., 1989; Rochelle Johnson, unpubl. data.
Tower Hill Main Lake	38° 19'	142° 22'	20	721	D'Costa et al., 1989;
Lake Cartearrong	38° 15'	142° 27'	75	727	Rhys Walkley, unpubl. data
Lake Wangoom	38° 21'	142° 36'	100	810	Edney et al., 1990
Lake Keilambete	38° 13'	142° 53'	120	759	Dodson, 1974
Lake Terang	38° 15'	142° 54'	130	796	D'Costa and Kershaw, 1995
Cobrico Swamp	38° 18'	143° 02'	140	847	Yesdani, 1970
Lake Gnotuk	38° 13'	143° 06'	200	820	Yesdani, 1970
Lake Bullenmerri	38° 13'	143° 06'	210	820	Yesdani, 1970; Dodson, 1979
West Basin	38° 19'	143° 27'	110	689	Gell et al., 1994
Lake Turangmoroke	37° 42'	142° 45'	220	516	Crowley and Kershaw, 1994; Ellyn Cook, unpubl. data

lakes to overflow, also influence salinity levels.

Lake Turangmoroke, in the northern part of the volcanic plains, differs in most respects from sites to the south. It is a shallow (c. 1m) hyper-saline lake formed in a depression within the basalt. Studies of sediments within and around the lake suggest that it was originally part of the Lake Bolac Basin that has been separated from Lake Bolac and defined by the formation of lunettes on the easterly sides of each lake (Jim Bowler pers. comm.). The Lake Turangmoroke lunette has also severed contact with Fiery Creek that skirts the southern shore and then flows

through Lake Bolac. Precipitation is much lower (540 cm per annum on average) than around the southern sites and, although it is the site at the highest altitude, falls within the temperature range of the other sites.

In general terms, the pre-European vegetation of the volcanic plains was composed predominantly of either grassland with a sparse but variable cover of eucalypts with *Eucalyptus camaldulensis* (red river gum) usually the most conspicuous, and perhaps including *Allocasuarina verticillata* (drooping shcoak), on the heavy clay soils weathered from older basalt



Figs 2a-c. Location of sites of pollen records in relation to reconstructed vegetation at the time of European arrival. Simplified from Anon (2000). Site names are shown in *italics*.

flows, and woodland dominated by a variety of *Eucalyptus* and *Acacia* species, *Allocasuarina verticillata* and *Banksia marginata* on younger, more pervious volcanic surfaces such as scoria cones and stoney rises. Both vegetation types show variation in relation to degree of drainage impedance. The volcanic plains are surrounded by a variety of parent materials that generally produce soil textures that are conducive to the development of open forests with grassy or heath understoreys. In the higher rainfall areas of the western highlands around Ballarat and particularly in the Otway Ranges, wet sclerophyll forest (or tall open forest) has developed. It is dominated by tall eucalypts with a distinctive understorey layer that includes tree Asteraceae and *Pomaderris aspera*. Small patches of *Nothofagus cunninghamii* rainforest occur in the highest rainfall part of the Otway Ranges.

As the location of sites in relation to particular communities has a major bearing on pollen representation, the vegetation within at least 20 km of each site is shown on Figs. 2a-c. Community distributions are based on the maps contained in Anon

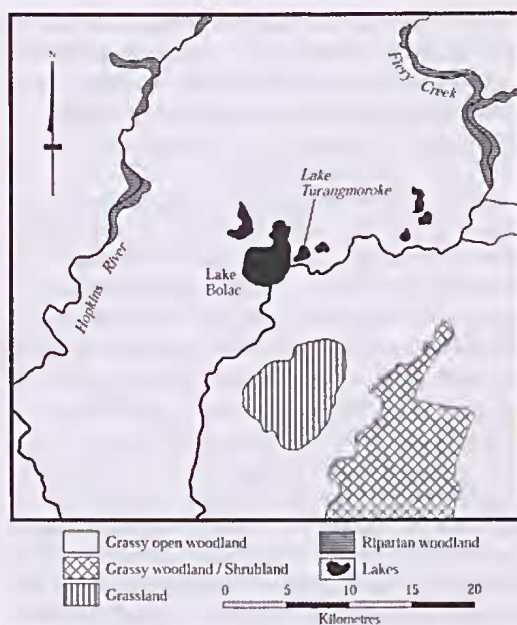


Fig. 2c.

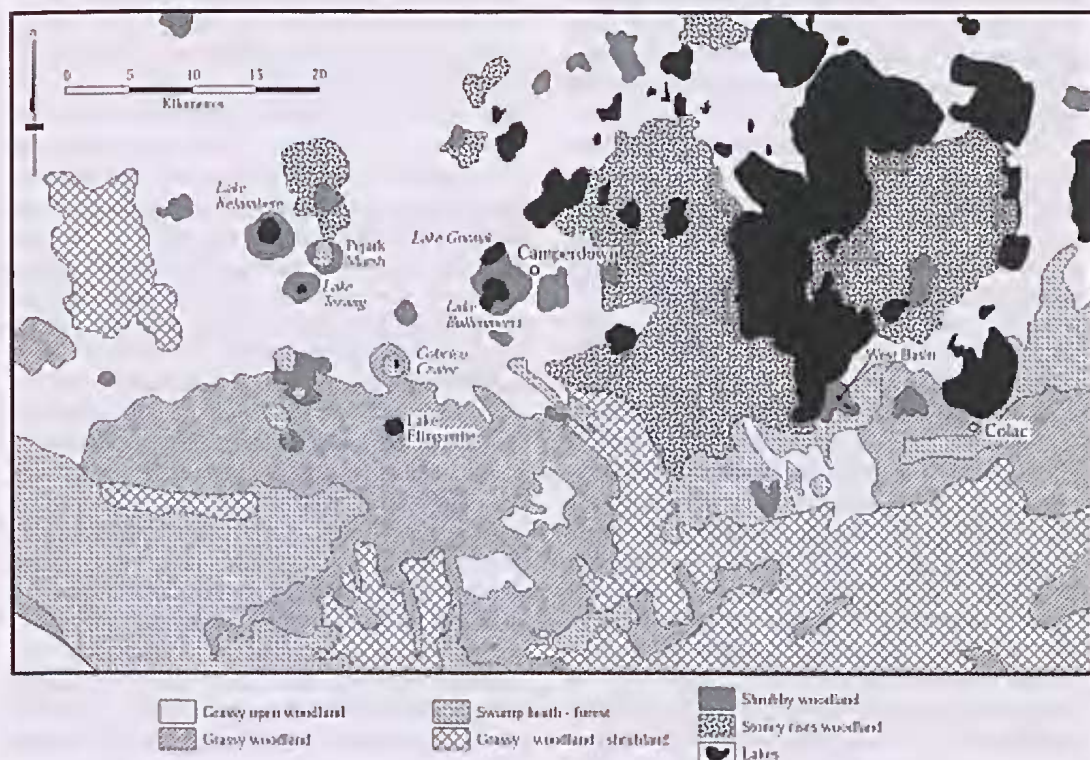


Fig. 2b.

(2000) and have been simplified for clarity and to emphasise the structural and floristic features that may strongly influence pollen representation. The three illustrated areas that incorporate all the sites are together representative of vegetation variation over most of the Western Plains.

Four sites are located on the Warrnambool Plain (Fig. 2a). In this area, a combination of coastal dune barriers and low-lying basalt flows, that have impeded the formation of coherent drainage, have resulted in extensive wetland or seasonal flooded vegetation communities away from the centrally-located Hopkins River catchment. These communities are grouped on Fig. 2a as swamp heath-forest. Tree canopies are composed of a variety of species with *Eucalyptus ovata*, *E. camaldulensis*, *E. viminalis* and *Acacia melanoxylon* predominant on basalt and *E. viminalis*, *E. baxteri* and *E. ovata* important on the less fertile and texturally lighter soils derived from Cenozoic marine and non-marine sediments. Understoreys are characterized by a significant sedge component within basalt communities, and a variety of heath and scrub species, including *Leptospermum* and *Melaleuca* spp., the heath form of *Banksia marginata* and *Allocasuarina paludosa*, as well as sedges, on lighter soils. Where drainage is sufficiently impeded to have formed peatlands and on low fertility soils, scrub and heath communities without a tree canopy can be found.

On the better drained parts of the basalt plain area, predominantly in the Hopkins catchment, grassy open woodland is the major natural vegetation type, as it is over the Western Plains as a whole. Canopy species are the same as those in more swampy basalt areas, but the ground layer is mainly composed of tussock grasses. Within this open woodland area are many small swamp areas that have not been included on Fig. 2a. A third major type of vegetation on basalt is shrubby woodland that characterizes the skeletal soils of well drained scoria and cinder cones as occur in association with Tower Hill and Lake Wangoom. Mapping of this vegetation type also appears to include tephra derived from explosion of the maars that may be largely derived from underlying limestone rather than scoria (Anon. 2000). It is debatable whether such deposits carried a similar type of vegetation. *E. viminalis*, *A. melanoxylon*, *Allocasuarina verticillata* and possibly the tree form of *Banksia marginata* were important components of the canopy layer above shrubs including *Bursaria spinosa* and *Hymenanthera* spp. and a ground layer of tussock grasses and/or *Pteridium esculentum*

(bracken). Some topographically more variable parts of the plains, possibly the result of differential weathering of relatively recent basalt flows, are mapped as grassy woodland-shrubland and contain an intimate mix of grassy woodland, grassy wetland and shrubby woodland.

Other vegetation types within this Warrnambool area include *E. viminalis* woodland, *Leptospermum lanigerum* swamp scrub and aquatic herblands. These form the coastal grassy woodland complex, essentially on Cenozoic sediments, that is considered to have had a canopy composed of a number of eucalypt species, but insufficient remains to fully describe its composition. There is also a small incursion of eucalypt-dominated open forest that is best represented in the overlapping map of Fig. 2b where most sites are located.

It is clear from Fig. 2b that, although pollen sites are concentrated on the open woodland basalt plains as in the Warrnambool area, this area has vegetation types indicative of additional environments. Swamp communities have reduced representation but open lakes, many of them saline to hyper-saline, are a major feature. This indicator of a poorly developed drainage system is largely the result of extensive recent extrusion of basalt flows that form a landscape of stoney rises. The woodland that has formed on this highly irregular terrain is dominated by a single species of eucalypt, *E. viminalis*, though often accompanied by *A. melanoxylon*, while woody Asteraceae are prominent in the shrub layer and tussock grasses and bracken are the common ground cover. To the south of the sites, on largely marine and coastal Cenozoic sediments, extensive grassy woodlands occur and give way to open forests as rainfall increases towards the Otway Ranges. These forests are dominated by *E. obliqua* with a number of other eucalypts including *E. willsii*, *E. aromaphloia* and *E. baxterii* variously present, while the understorey is usually rich in shrubs. Swamp heath-forest occurs in patches on both basaltic and non-basaltic soils, and is or was present in some maar crater swamps such as Cobrico Crater, Pejark Marsh and probably Lake Terang. Shrubby woodland is considered to have existed around all the maar pollen sites though most sites lack substantial scoria sediment.

The largely basaltic area around Lake Turangmoro (Fig. 2c) is dominated by grassy open woodland but dotted with depressions supporting freshwater wetlands with sedges prominent beneath the open eucalypt canopy, and brackish to saline lakes or salt pans of which Lakes Bolac and Turangmoro

are among the most conspicuous. Occasional rises support shrubby woodland, while riparian woodland of *E. camaldulensis* with an understorey of grasses, sedges and aquatics, is prominent along stream channels including Fiery Creek that flows into and out of Lake Bolac. Other communities include grassland where trees are extremely scattered due to a combination of the heavy soils and seasonal waterlogging, and grassy woodland-shrubland where there is increased topographic variation.

Throughout the Western Plains there has been substantial alteration of vegetation since the arrival of Europeans and, with the exception of a few environments such as the stoney rises where technology for substantial agricultural production is only just developing, the representation of intact native communities is rare. As a result of agricultural activities, combined with the high degree of variation in this geologically recent landscape, reconstruction of the 'natural' vegetation is very tentative. Of particular concern for this paper is the uncertain location of some key taxa, although examination of the pollen records may contribute to some better understanding of their natural abundance and distribution.

## METHODS

### *Pollen data selection*

For each pollen record, values of selected taxa of the dry land component were extracted from available raw data or, in the cases of Lake Keilambete, Lake Bullenmerri and West Basin, measured from published diagrams and recalculated on a 'common' taxon pollen sum for each spectrum (see Figs. 4a-k). These common taxa are demonstrated to reflect variation in the regional vegetation of southeastern Australia (Kershaw et al. 1994; D'Costa & Kershaw 1997). They include the following: *Eucalyptus* and Casuarinaceae as dominants of sclerophyll forest and woodland; *Acacia*, *Banksia* and *Dodonaea* as other notable and widespread woody representatives of sclerophyll vegetation; *Pomaderris* (specifically the *P. aspera/apetala* pollen type) that characterizes the understorey of many tall open (wet sclerophyll) forest communities; *Nothofagus* and *Phyllocladus* that typify cool temperate rainforest; and Poaceae, Asteraceae (Tubuliflorae) and native *Plantago* that are major components of the understorey of open sclerophyll forests and woodlands and are dominants of treeless communities such as grasslands and

herbfields. Within the Asteraceae (Tubuliflorae) a distinction is made between plants producing pollen with conspicuous spines, that embrace almost all extant forms within the region, and those producing pollen grains with very short spines (Asteraceae type b). The plant sources of Asteraceae type b are uncertain and are recorded mainly in glacial-aged sediments (Macphail and Martin 1991). Chenopodiaceae and *Callitris* values were also calculated for some diagrams as these can contribute substantially to the regional pollen rain. However, they have been expressed as percentages relative to, rather than as a component of, the pollen sum because, in the case of Chenopodiaceae, there can be major overrepresentation from saltmarsh vegetation growing within or around saline basins and, in the case of *Callitris*, the pollen grain has not been recognised in a number of studies. In addition, *Callitris* pollen cannot be separated from that of introduced Cupressaceae species, including the commonly planted Cypress pine. In several early diagrams (i.e. the records from Cobrico Crater and Lake Gnotuk and last 8000 years from the Lake Bullenmerri record) comparability is reduced by the failure to identify grains of one or more of the taxa native *Plantago*, *Dodonaea* and *Pomaderris* that together may make up around 10% of the pollen sum in other diagrams. It is also notable that Asteraceae type b was not separated from other Asteraceae throughout the Bullenmerri record.

### *Analogue matching*

Analogue matching, using the techniques of Overpeck et al. (1985), is employed to provide a measure of the degree to which past vegetation relates to vegetation represented at the time of European settlement and to provide estimates of precipitation changes through time. The latter will be used in an assessment of the relative importance of climate in vegetation change while the former will provide some measure of community integrity through time and a basis for assessment of the validity of the climatic estimates. With the analogue technique, each fossil spectrum is compared with a data base of recent pollen spectra, in this case those spectra derived from just prior to evidence for European settlement within sites included in the southeastern Australian pollen data base (SEAPD) (Kershaw et al. 1994; D'Costa & Kershaw 1997) but excluding 24 sites considered inappropriate for climate reconstruction (*sensu*

D'Costa & Kershaw 1997). These excluded sites included those where fluvial influences are significant or where the uppermost sediments were disturbed. Following this process the SEAPD consisted of 112 sites. Modern precipitation estimates for all sites have been determined from climatic prediction system BIOCLIM (Busby 1991).

Canonical Correspondence Analysis (CCA), a multivariate technique which assesses the explanatory power of multiple environmental variables (Palmer 1993), was implemented to provide closest recent analogues for fossil spectra and to assess the suitability of annual precipitation for climate reconstruction. The computer program MAT (Juggins 1995) was used to compare the predictive power of 20 (dis)similarity measures for assessing the degree of similarity between assemblages (with varied emphasis on abundant vs. poorly represented taxa), including all those measures outlined in Overpeck et al. (1985). The program was also used to determine the optimal number of analogues to use in predicting modern climate. The predictive power of similarity measures was assessed using the Root Mean Square Error (RMSE) between modern and pollen predicted climate.

Although mean annual rainfall (RANN) was the variable chosen for palaeoclimatic reconstruction, all other BIOCLIM generated precipitation variables, with the exception of their range, were highly correlated ( $r^2 > 0.85$ ) for sites in the SEAPD and as a result mean annual rainfall can be regarded as a proxy for other measures, that are essentially different estimates of rainfall seasonality. CCA showed that RANN explains 17.9% of significant ( $p < 0.005$ ) variance in the SEAPD, which is marginally less than that explained by the most important variable, precipitation of the driest quarter (18.6%), with which it is highly significantly correlated ( $r^2 = 0.94$ ,  $p < 0.005$ ) (Tibby et al. 2001). This level of explained variance is comparable to, or exceeds that in many other transfer function studies and therefore RANN is an appropriate variable for which to derive a transfer function. As a result of the aforementioned strong co-variation between precipitation variables, other precipitation measures explain little variance ( $< 3.5\%$ ) not already explained by annual precipitation. Similarly, mean annual temperature (and other temperature measures) explain only a small proportion of variance (3.4%) in addition to annual precipitation. As such the SEAPD is unsuitable for reconstructing temperature parameters independent of precipitation with any confidence.

Kershaw et al. (1994) suggested that chi-squared distance would be the most appropriate to infer past climates from the SEAPD since it places less emphasis on rare taxa (which may have been inconsistently identified by the multiple contributors to the data base). Tibby et al. (2001) showed, in terms of its ability to predict modern climate from pollen assemblages, that squared chord distance (SCD) has errors which were marginally lower ( $\approx 3\%$ ) than those associated with the chi-squared technique and has the highest predictive ability of 20 (dis)similarity measures compared.

Tibby et al. (2001) also assessed the effect of number of analogues used on model predictive error. They showed that errors declined with addition of sites up to between 3–6 sites, but that the addition of subsequent sites (which presumably were poorer analogues to the site being estimated) increased errors in the model. Where SCD is the similarity measure

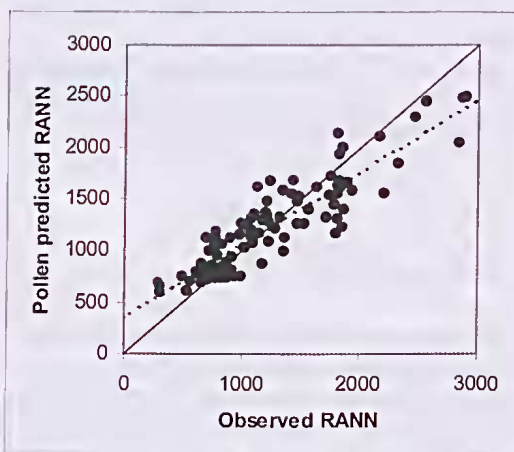


Fig. 3. Observed v. pollen predicted annual precipitation (RANN) in the 105 site south-east Australian pollen data base. Shown is both the line of equivalence (solid) and the linear trend (dotted) in the data.

used, lowest errors occur when three sites are used (providing support for the approach adopted by D'Costa (1997) and Harle (1998)). Hence for the purposes of reconstruction (and reporting of model errors), the weighted average of RANN in the three sites with lowest SCD was used. Comparison of modern RANN with pollen predicted RANN in the 112 site data set showed that, although there was a reasonable relationship between the observed and predicted data ( $r^2 = 0.70$ ), RMSE, was substantial (398 mm). As a result we excluded seven sites with the greatest residual difference between observed and inferred values. The removal of these sites led to substantial improvement in the model with the RMSE

almost halved to 244 mm and the  $r^2$  increased to 0.84. As can be seen from an examination of Fig. 3, there is reasonable agreement between pollen predicted and observed RANN although, as illustrated by the trend line, there is a tendency for RANN to be overpredicted at the low values and underpredicted at high values. This is the case with many transfer function models (Birks 1998) and is a product in part of an edge effect where the environmental gradient is truncated before the full breadth of a taxon's distribution is sampled.

The relatively small error highlights the importance of precipitation in influencing the distribution of dryland vegetation in south-eastern Australia. This low level of error is particularly pleasing since the source of much of the 1- $r^2$  error may be derived not from a poor biological relationship to the environment, but rather from inadequate characterisation of the environment. This is particularly relevant in this situation since the BIOCLIM derived estimates of RANN at the site selected have errors of their own. Furthermore, the BIOCLIM estimated of RANN represent a contemporary estimate, while the pollen estimates are derived from pollen data often > 200 years old. Given that precipitation may have considerably altered in south-east Australia over that period (Jones et al. 2001), pollen predictive errors may derive from the mis-match between biological and environment sampling.

#### *Establishment of chronologies*

Radiocarbon dates, together with the first presence of exotic pollen (considered to have occurred approximately 150 years BP), provide the basis for establishment of chronologies. In those records containing several radiocarbon dates and where the nature of the sediments suggests continuous and relatively constant deposition, radiocarbon timescales have been estimated from linear interpolation between dated points. These independent timescales are valuable for temporal comparison of changes between records. In parts of records where dating is uncertain, comparison with more certainly dated records is employed to provide general estimates of regional change, though this circularity restricts assessment of spatial variation in the timing of particular events. In the case of Lake Turangmoro, where periods of non-deposition are suspected, no attempt has been made to estimate a timescale. In the longest dated record, that from Northwest Crater, the radiocarbon

timescale has been calibrated (Stuiver & Reimer 1993) to provide a calendar year timescale for those interested in comparisons with calibrated records from other areas.

### VEGETATION AND ENVIRONMENTAL RECONSTRUCTION

#### *Pre-Holocene*

Three records, Northwest Crater (Fig. 4a), Lake Bullenmerri (Fig. 4i) and Lake Turangmoro (Fig. 4k) provide substantial evidence of Late Pleistocene vegetation. Other sites either contained sediments too consolidated to core or revealed essentially inorganic sediments that did not preserve pollen. In either case substantially drier conditions than today may be inferred. It is not difficult to explain the persistence of the record at Lake Bullenmerri because, being the deepest lake in Victoria, lower water levels would have been insufficient to dry the basin, but the situation is not as simple at the other two sites. There is certainly evidence for lower, variable lake levels at Northwest Crater and presumably here the ground water level remained sufficiently high to just maintain a lake despite an absence in the surrounding Main Lake of Tower Hill, with which it has a ground water connection (D'Costa et al. 1989). It is very surprising that there is a record from the shallow, hyper-saline Lake Turangmoro, the site experiencing the lowest rainfall. However, it is the only site potentially river fed, if Fiecy Creek did flow into the basin, and it is unlikely that the record is continuous as a date of 12,640 years BP from the neighbouring Lake Bolac lunette indicates deflation of lake sediments from the Bolac basin, at least around this time (Crowley & Kershaw 1994). The date is consistent with a proposed break in deposition of the lake sediments at 132 cm (Crowley & Kershaw 1994).

The vegetation of the Late Pleistocene phase is characterised by a predominance of herbaceous and woody/herbaceous taxa with Poaceae and Asteraceae dominant and *Plantago*, Chenopodiaceae and Asteraceae type b, where separated from Asteraceae (i.e. Northwest Crater), conspicuous. Woody taxa have total percentages of around 20-25% or less. The vegetation has been described as predominantly steppe-grassland with no modern analogue (Kershaw & Bulman 1996), and this interpretation is supported here by the high analogue distance values. Trees may

have formed an open canopy cover or, most likely, were restricted to isolated, sheltered pockets.

There is both temporal and spatial variation in the pollen data. Those samples beyond about 15,000 years ago in Northwest Crater and Bullenmerri, and perhaps the basal 3 samples of Turangmoro, represent the Last Glacial Maximum. Here *Asteraceae* is predominant at Turangmoro, equal with *Poaceae* at Northwest Crater and subordinate to *Poaceae* at Bullenmerri. These data indicate variation in grassland steppe vegetation but its significance is unknown. The much lower values of *Eucalyptus* around Lake Turangmoro than around the other two sites may suggest greater survival in the southern part of the plain. Conversely, higher values for *Casuarinaceae* at this site may indicate more substantial regional survival of woodland trees (represented in this area by *Allocasuarina verticillata*). However, the high proportion of small *Casuarinaceae* grains suggests a heath source, probably *Allocasuarina paludosa* growing around the lake. The relatively high values for *Banksia* at Northwest Crater more certainly indicate a more local source, as *Banksia* pollen is poorly dispersed. In this largely treeless landscape, it is likely that the shrub form of *Banksia* formed a major component of a heathland on the scoria cones. The fact that there is little representation of this taxon at the other sites could be due to an inability to disperse into the centre of larger lakes, but its poor representation relative to Holocene assemblages at these sites suggests that conditions were not suitable for the formation of local *Banksia* heath. *Callitris* pollen forms a higher proportion of Pleistocene than Holocene assemblages at both Bullenmerri and Northwest Crater. One interpretation is that the well dispersed pollen type is derived from Wimmera and Mallee sources to the west and north of the area and its representation is increased because of low production from a sparse tree cover on the plains. However, it might be expected that values would be highest at Turangmoro, and the record from here (supported by more recent work by one of us – EC) indicates very low pollen representation during the latest Pleistocene. If the *Callitris* values are a true indication of parent plant representation in the landscape and not an artefact of preservation, then perhaps the taxon did have a presence on the plains at this time. The existence of isolates of *Callitris* today on the eastern fringes of the basalt plains indicates the possibility of a more extensive past distribution on basalt, and the fact that rainfall on the eastern fringes is about 200 mm less than at

Bullenmerri today is consistent with a presence there during the last glacial period (or perhaps more especially the very late Pleistocene).

The evidence for existing vegetation supports sedimentological data for conditions, on average, being drier than today. However, lowest estimates from analogues, ranging from about 100 mm lower than today at Turangmoro to perhaps 200 mm lower than today at Northwest Crater, would not result in treeless conditions. Conversely, the estimate of a mean annual rainfall of only 250 mm derived from fossil material of the red kangaroo, *Macropus rufus*, at Lake Bolae within this period (Horton 1984) would be a different proposition. The pollen records from the Western Plains reveal little about temperatures but both a general palaeoclimate model for south-eastern Australia (Harrison & Dodson 1993) and palaeoecological data (Kershaw 1998) indicate that temperatures are likely to have been about 4°C lower than today, again insufficient, even in combination with lower rainfall, to account for the scarcity of trees. In fact, lower temperatures would have increased the effectiveness of precipitation. Consequently, other factors such as higher wind speeds and incursions of cold polar air (McGlone 1998) and, more recently, low carbon dioxide levels that increase the competitive advantage of grasses (Huang et al. 2001), have been invoked to explain the paucity of trees at these latitudes. The expansion of the continental shelf with glacial low sea levels would also have impacted on climate with the area suffering greater continentality, so greater variation between summer and winter may have been an additional important factor. It has been suggested for a similar situation during the glacial period in the Mediterranean region, where there was sufficient water to form lakes but within a treeless landscape, that excessive rain during the winter filled the lakes and that evaporation in the relatively warm but extremely dry summers resulted in a water deficit sufficient to exclude tree growth (Prentice et al. 1992).

After about 15,000 years BP there is evidence of some change within the vegetation. The pollen of woody taxa essentially maintains its representation

Fig. 4a–k. Major features of Late Quaternary pollen records from the Western Plains of Victoria and results of analogue matching. All taxa are expressed as percentages of the 'common' taxon sum for each sample. The horizontal dashed line marks the first presence of exotic pollen while vertical dashed line indicates the present day mean annual precipitation of the site, on each diagram. Min d<sup>2</sup> is the distance between each sample and its numerically closest recent analogue. Chronologies derived by interpolation between radiocarbon dates.

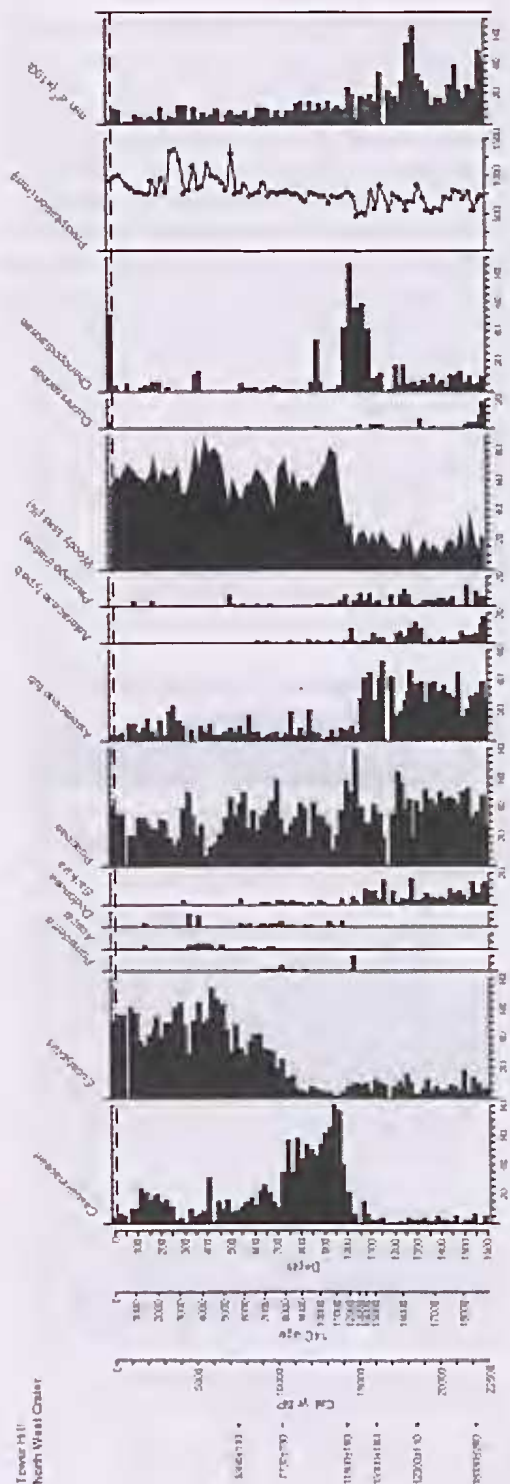


Fig. 4a.

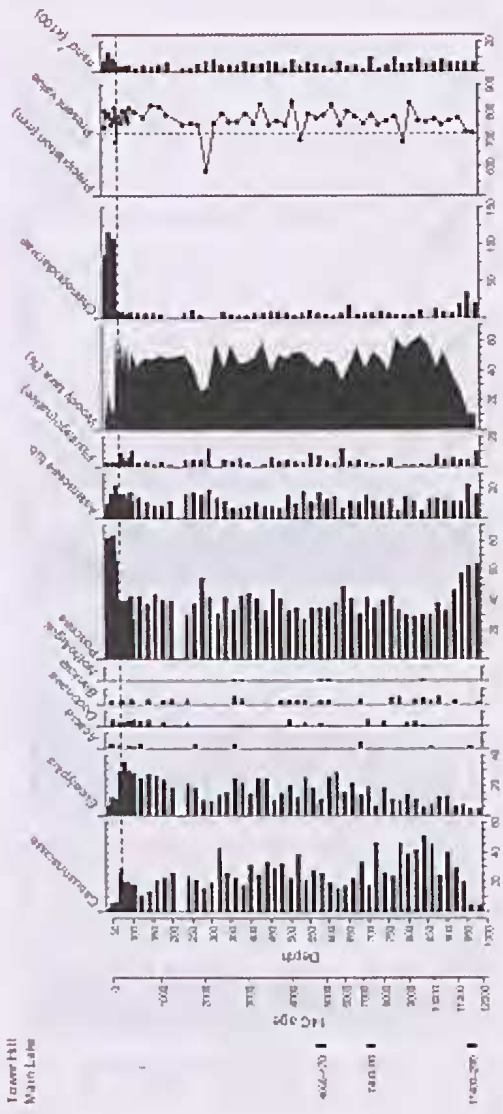
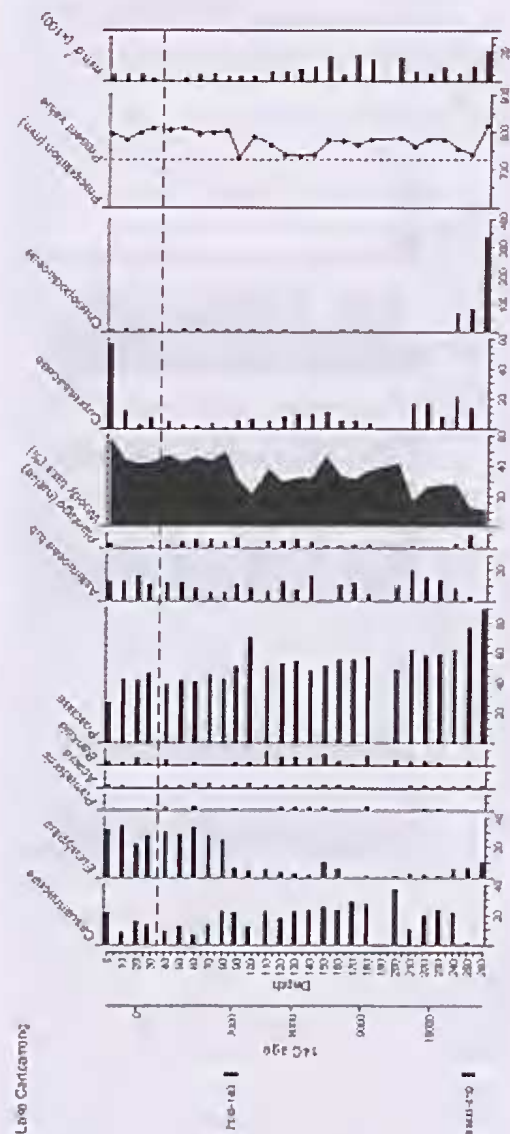


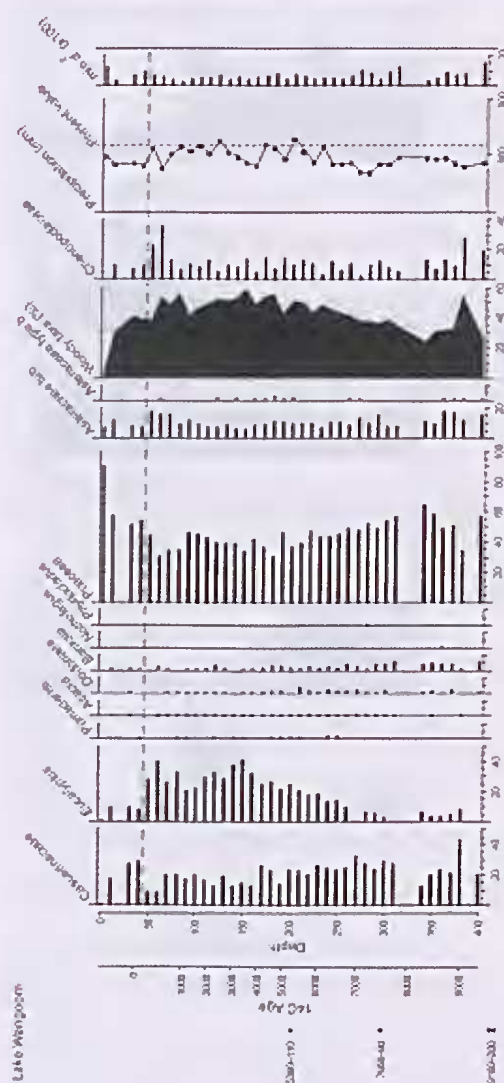
Fig. 4b.

at Northwest Crater, falls a little at Bullenmerri but perhaps increases at Turangmorohe, although the dating is uncertain at this site. This increase, though, is largely in heath *Casuarinaceae* (Crowley & Kershaw 1994) and does not indicate a regional increase in trees. In all diagrams there is a rise in *Poaceae* values relative to those of *Asteraceae*, gradually at Bullenmerri, more abruptly at Turangmorohe, and sharply at Northwest Crater. The change at Northwest Crater is dated to between

13,000 and 12,000 years BP and falls within a major peak in Chenopodiaceae. The two events are likely to be connected. The relative increase in grasses relative to Asteraceae is likely to reflect an evolution of steppe vegetation into grassland with temperatures increasing towards present levels while the Chenopodiaceae indicate an effective reduction in moisture in response to the temperature increase. Any rise in precipitation would have lagged that of temperature because of a slow response of sea surface temperatures and ice sheet melting (and hence sea level rise) to global warming. The extent of the



*Fig. 4c.*



*Fig. 4d.*



'amelioration' is indicated by initiation of a forest or woodland cover in the region from about 12,000-11,500 years ago. At Bullenmerri, there are notable increases in Casuarinaceae and *Eucalyptus* at this time with an increase in total woody plant representation from about 20% to at least 30% while at North-west Crater Casuarinaceae percentages rise sharply to over 60% with eucalypts actually having reduced values. The base of the record in Tower Hill Main Lake shows a presumably synchronous increase in Casuarinaceae to 40%. Climatic estimates show a sustained increase in precipitation at this time and some support for a rainfall increase is provided by the initiation of organic sediment accumulation and a reduction in Chenopodiaceae values at Main Lake,

but high chenopod values are maintained at North-west Crater, and also Bullenmerri. It could be suggested, especially in light of reductions in Asteraceae values, that the Casuarinaceae expansion could have been triggered as much by temperature as by precipitation related factors.

The subsequent beginning of organic sedimentation, and hence permanent lake establishment, at sites provides some indication of the nature of effective precipitation increase within the transition. Those sites with relatively reliable basal dates indicate a progressive rise in effective rainfall from 11,400 years BP to 8000 years BP. Basal ages generally relate to basin depth with deeper lakes such as West Basin (c10,600 years BP) and Lake Keilambete (c 9700 years BP) being older than the shallow basins of Lake Wangoom (c 9200 years BP) and Lake Terang (c 8000 years BP). The basal age determination for Lake Gnotuk ( c 9000 years BP), of similar lake depth to

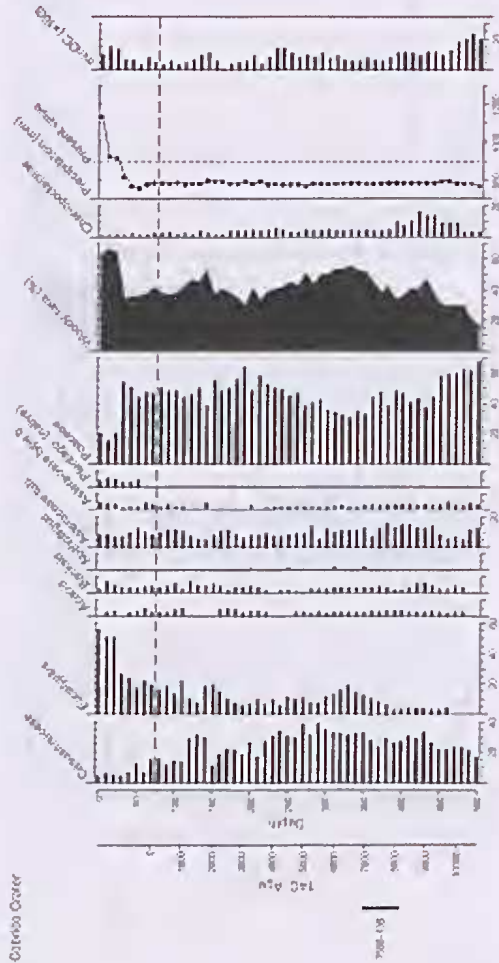


Fig. 4g.

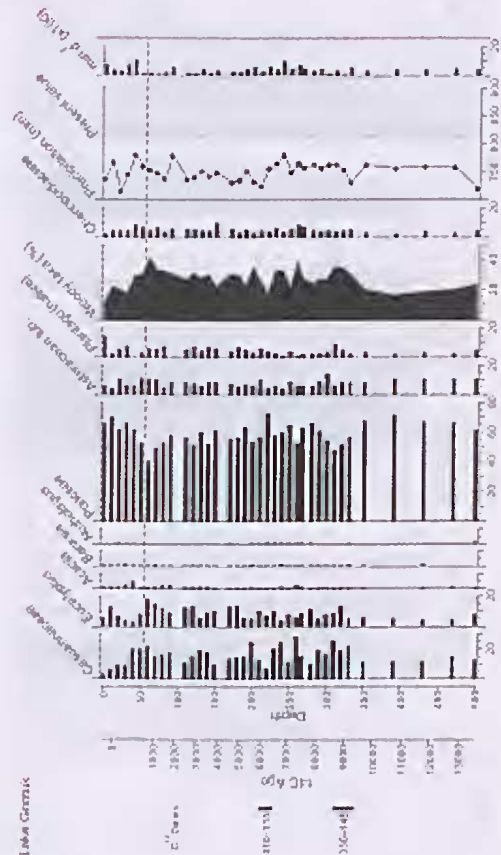


Fig. 4h.

Lake Keilambete, is problematic in that there appears to be mixing of sediment with volcanic ash below this date. Other exceptions to this pattern are the shallow lake sites of Tower Hill and Lake Cartcarrong whose older dates could suggest that the southwestern part of the plains experienced relatively higher rainfall than the southeastern part in the late Pleistocene, a situation that might have arisen through closer proximity to the sea. Alternatively, there may have been a higher ground water table. The progres-

sively wetter conditions though are not reflected in the analogue precipitation estimates that show, on average, constant rainfall levels through the transition period.

In line with the lake establishment data, there is variation in the timing and extent of development of Casuarinaeae, presumably *Allocasuarina verticillata*, between sites during the transition. Of those sites where values of the taxon rise substantially, those at Tower Hill are clearly the earliest,

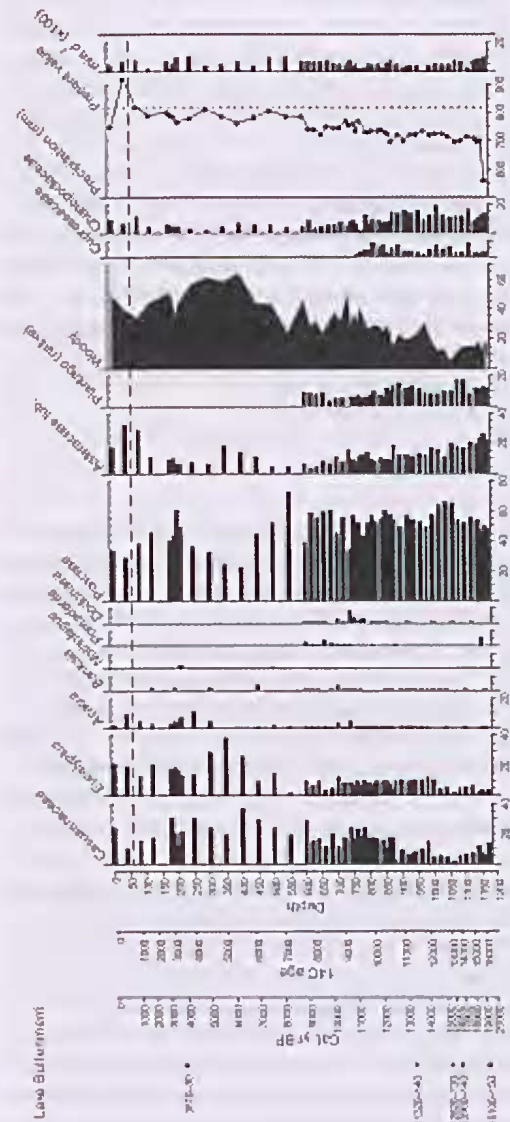


Fig. 4i.

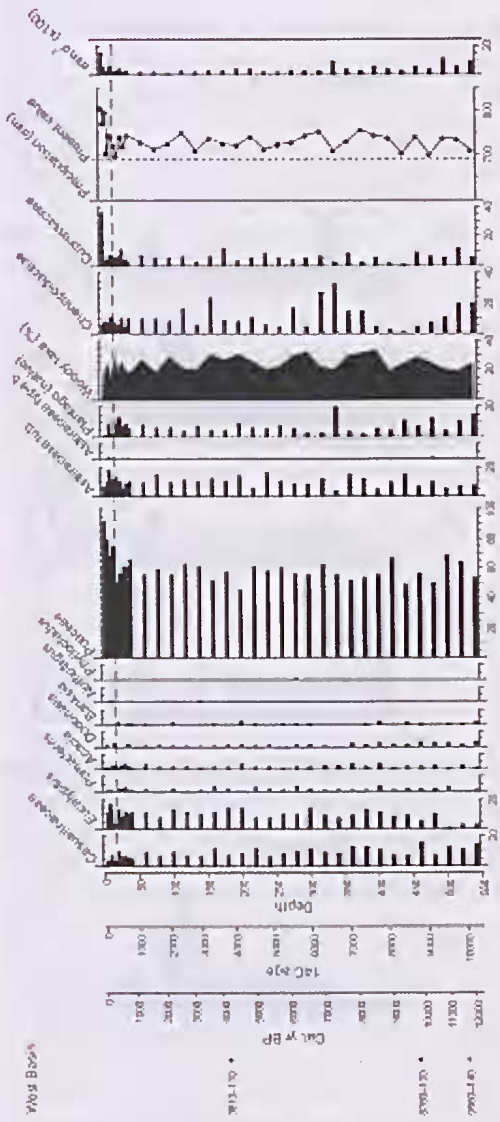


Fig. 4j.

about 11,500 years BP, followed by Cartcarrong (c 10,500 years BP) and Lake Turangoroke (c 9000 years BP). These sites are also the only ones where Casuarinaceae forms a major peak in the transition or early Holocene. Lake Bullenmerri shows a second and more notable rise in Casuarinaceae about 10,500 years BP. Casuarinaceae values have presumably risen at all other sites before record commencement and, considering the geographical proximity of these sites to Lake Bullenmerri, increases

around the same time (c 10,500 years BP) might be expected. With respect to the reason for this pattern of expansion, the proposed existing rainfall gradient may have been important, as may have been centres of taxon survival during the last glacial period. *A. verticillata* appears to prefer well drained sites, including dune systems and basalt rises, but is also widespread within grassy woodlands in the region, in association with eucalypt species. The low values for pollen that can be attributable to *A. verticillata* during the last glacial period would suggest an absence on the plains, despite availability of well drained scoria material around some sites, especially those of Tower Hill. It might appear then that the early expansion around Tower Hill was from refugia within the dune systems in the Warrnambool area, primarily as a result of an increase in temperature, with subsequent migration, from this source, over the southeastern part of the plains. In the case of Lake Turangmoroke, late colonisation but marked representation may have been a result of a combination of time for migration from the southern margin of the plains and optimal conditions for establishment. Alternatively, the source of Turangmoroke populations may have been the uplands to the north and north-west of the area.

### The Holocene

By the beginning of the Holocene, pollen values suggest that woody plants were as well established on the southern part of the plains as they were at the time of European arrival, except perhaps in the north where, if the dating in the Lake Bolac basin is accurate, full development was delayed for about 1000 years. In the case of the Bullenmerri record, the ratio of woody to herbaceous plants is distorted by the lack of recognition of native *Plantago* within the Holocene sequence. In addition to the noted representation of Casuarinaceae, *Banksia*, *Eucalyptus* and *Callitris* in the Pleistocene, *Dodonaea* gained a regional representation around 10,000 years ago, suggesting some increase in diversity. There is evidence also of forest expansion in wetter areas, with fairly consistent representation of the wet selerophyll taxon *Pomaderris*, and occasional representation, at a number of sites, of the rainforest taxon *Nothofagus*. The highest values or most frequent occurrence of these taxa at West Basin suggests an Otway Ranges source but the presence of *Phyllocladus* pollen in a few records, whose parent rainforest plants are not present today on the

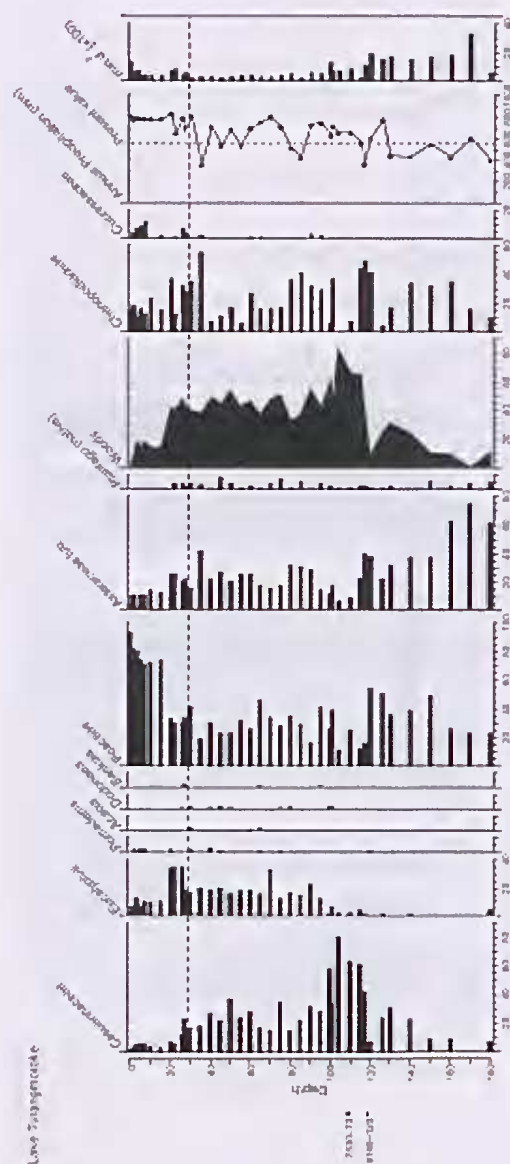


Fig. 4k.

Australian mainland, may indicate also longer distance transport from Tasmania. Within the Lake Bolac region, there is little indication of the local presence of *Eucalyptus* until about 10,000 years BP and a lack of evidence for *Acacia* or *Dodonaea* until about 7000 years ago.

The average value of woody plant pollen through the Holocene varies from site to site, but does generally reflect regional tree or shrub cover. Some variation can be accounted for by regional differences, but, despite significant pollen transport ability of the major tree taxa, much of it relates to the nature of individual sites. With the twin lakes of Gnotuk and Bullenmerri, the latter has an average woody pollen value of 45%, 20% above that at Gnotuk. This difference can at least partially be explained by higher dispersal ability of tree pollen and hence higher representation in a core from the centre of the larger lake. Conversely at Tower Hill, the small basin of Northwest Crater has 65% woody pollen, the highest average percentage of any site, while Main Lake less than 1 km away, averages 50%. In this case the fact that Northwest Crater is surrounded by scoria cones with a substantial woodland cover and Main Lake is exposed to the open woodland of the plains, has probably been the dominating influence on pollen representation. It is perhaps surprising that West Basin, along with Keilambete and Gnotuk, has the lowest woody plant pollen percentages, despite having closest proximity to forest vegetation. Although there are notable percentages of wet forest taxa indicating forest as a pollen source, the predominant westerly winds may have generally limited its overall representation. Also unexpected is the relatively high value of 40% for woody plant pollen at the driest site, Lake Turangmoro. Here, a relatively high representation in the landscape of Casuarinaceae, a taxon that depends on wind as the sole mechanism of pollen dispersal and consequently has high pollen production, may have been important.

The substantial differences in proportions of woody plant pollen between sites do not appear to have unduly impacted on the quantitative precipitation estimates, at least for the records from the southern part of the plains. In fact Holocene averages for all sites, excluding Lake Turangmoro, fall within 80 mm of present day estimates with half within 20 mm. Overall, spatial variation in rainfall between site extremes is reduced from 160 mm at the present day to a Holocene average of 50 mm. Overestimates are recorded for sites within the Warrnambool region (Main Lake, Northwest Crater and Cartarrong)

and West Basin and these could be due to high regional ground water tables that increase effective moisture availability to plants and proximity to forest vegetation of the Otway Ranges, respectively. All sites in the middle of the southern plains show rainfall underestimates, perhaps because of some impedance to tree growth by the heavy textured soils. The estimate from Lake Turangmoro (680 mm) is substantially higher than the present day value of 540 mm. The reason for this discrepancy may be statistical since the method overestimates values for sites with lower rainfall and there are few sites with similar rainfall characteristics from which to draw analogues. The regional importance of Chenopodiaceae around Lake Turangmoro, that is excluded from the pollen sum, together with a more open grassy understorey, may also contribute since it has resulted in a higher relative abundance of pollen from woody plants than is the case generally within the SEAPD.

The most notable change in the vegetation over much of the plains within the Holocene is an increase in *Eucalyptus* relative to Casuarinaceae. This change is marked in the records from the western part of the region (Tower Hill, Cartarrong, Turangmoro and Wangoom) where there is some clear, partial replacement of Casuarinaceae by *Eucalyptus* beginning around 8000 to 7000 years ago. Most other records show a similar but more subdued change around the same time. The exceptions are Keilambete, Gnotuk and West Basin where there is little change in the representation of these two taxa after the initial rise in *Eucalyptus* in the very early Holocene.

The reasons for the partial replacement of Casuarinaceae by *Eucalyptus* can be debated. If taken in combination with the general evidence for increased woody plant diversity through the early Holocene, it is possible that this change was the result of an increase in rainfall. There is also the possibility that there was a critical reduction in temperature around 7500 years BP as, from the SEAPD, Casuarinaceae percentages are highest under present day warmer as well as drier environments than are those of *Eucalyptus*. An increase in effective precipitation, whatever the contributions of absolute rainfall and temperature, are certainly indicated in reconstructions and models of lake levels within the region (see Jones et al., 1998). These indicate a rapid increase in effective rainfall between 8000 and 7000 years ago that would explain the degree of synchronicity of change within the various records. However, it is still surprising that there was similar and synchronous response at the drier site of Lake

Turangmoro and this may suggest the involvement of other climatic, or non-climatic influences. It has been proposed, from an application of the analogue technique to Northwest Crater (Kershaw & Bulman 1996), that there was a shift in partial-analogues from sites within the more western part of southeastern Australia, that experience a Mediterranean type of climate, to those in the east where seasonality is reduced. Consequently, the early Holocene may have seen some alteration in atmospheric circulation that resulted in the westerly contraction of a Mediterranean climate, which had dominated the western part of plains and extended inland to Lake Turangmoro and facilitated the expansion of Casuarinaceae. An additional factor may have been an increase in waterlogging over the plains with an increase in precipitation, whether annually or seasonally, and waterlogging is a feature that has been shown to be widespread today. Both a decrease in seasonality and increase in water table height would be consistent with a replacement of *Allocasuarina verticillata* by eucalypt species in some areas (Crowley, 1994a) as *A. verticillata* has greater drought tolerance as a result of its deep root penetration (e.g. Withers 1978) while some *Eucalyptus* species have relatively high transpiration rates that allow them to survive high groundwater tables (e.g. Biddiscombe et al. 1985). Another explanation would be that an increase in burning, possibly resulting from more intensive Aboriginal occupation and use of the plains, would have favoured eucalypts over the relatively fire sensitive casuarinas. However, there are few charcoal records available for testing this idea and, those that exist, provide no support for it. In fact, evidence for occupation of this region by people suggests a reduction at this time with major intensification occurring after 4000 years BP (Lourandos & David 2002). Although a climatic cause for the increase of *Eucalyptus* relative to Casuarinaceae appears most likely, the quantitative climatic reconstructions fail to provide any supporting evidence. Incorporation of measures of seasonality may have been useful, but, as mentioned, these are highly correlated with mean annual precipitation in the SEAPD.

There is little indication of sustained variation in regional vegetation, from the pollen data, between 7000 years BP and the arrival of European people. Despite the evidence for highest water levels in lakes between about 7500 and 5500 year ago (Jones et al. 1998), only a few records from the central part of the plains (Keilambete, Cobrieco and Bullenmerri) reflect

the higher precipitation levels through a minor peak in woody plant values, while a number of sites show maximum representation of *Eucalyptus* within the last 5000 years. Precipitation curves, despite some fluctuations, are also stationary, apart from those at Bullenmerri and Northwest Crater that display overall higher values. The latter record also shows a high level of variation in the last 5000 years. The change here corresponds to a replacement of open water by swamp vegetation in the basin that could be construed as indicating a reduction in water level and therefore evidence for decreased rather than increased precipitation. It is possible that the apparent precipitation increase is an artefact of the altered pollen deposition surface. The displayed climate variation may indicate the sensitivity of the vegetation around the site to El Niño-Southern Oscillation (ENSO) variability that has been suggested to have become more pronounced in the last 5000 years from other proxies on the Western Plains and from other parts of eastern Australia (McGlone et al. 1992). Alternatively the variability may simply reflect changing analogue matches between recent sites in the SEAPD with similar pollen spectra but somewhat different climates, as is probably the case with many of the fluctuations in rainfall curves in all records. Higher resolution records with greater dating control are needed to see if there is systematic climatic variation during this period.

#### *European settlement period*

The first presence of exotic pollen, particularly *Pinus*, is used to indicate European settlement, dating from about 1840 AD, though landscape impact is likely to have preceded the establishment of these plants. From a detailed study of the topmost sediments at one site, Cobrieco Crater, it can be seen that the effects of European settlement included tree clearance and planting and establishment of pastoral and arable agriculture. Dodson et al. (1994) found that *Eucalyptus*, Casuarinaceae and Poaceae were the only regional taxa to show significant change between the historic and immediate prehistoric periods. The data set considered here suggests that these taxa, with the addition of *Plantago*, are also the ones that were most affected regionally although patterns of change are variable between sites. This variability is presumably related mainly to different degrees of impact and history of land management, but sample resolution will also influence event recognition. All sites

except Bullenmerri and Wangoom show a sustained decline in Casuarinaceae, and many sites indicate that this decline occurred early in the settlement phase. This decline is attributed to preferential selection of *A. verticillata* for firewood and its vulnerability to fire (Crowley & Kershaw 1994). There is evidence from Turangmoroke for an increase in charcoal in the early settlement period while higher charcoal levels are indicated for the settlement period generally at the Tower Hill sites and Cobricio. Dodson et al. (1994) suggest that the impact of burning was increased by a change from the low intensity, frequent burning regime of Aboriginal people to a less frequent but more intense fire regime that developed after settlement.

*Eucalyptus* tends to decline after Casuarinaceae, where sample resolution allows separation, and is generally associated with an increase in Poaceae. This combination can be best attributed to woodland removal with the development of more intensive agriculture, often cultivation in the early days. At Turangmoroke and Gnotuk, there is evidence for an initial increase in eucalypt values before the decline, and this may have been a response of eucalypts, either in terms of increased regeneration or flowering, to the reduction of Casuarinaceae. At Cobricio, the strong increase in eucalypts in the late European period may result from recent planting, as suggested by Dodson et al. (1994), while much variation in records could result from a combination of clearing for agriculture and establishment of windbreaks. High values for Cupressaceae pollen in some records indicate the extensive planting of Cypress pine rather than any increase in native *Callitris*.

Despite the creation of more extensive grasslands, there is a reduction in native *Plantago*. The demise of this herbaceous taxon is probably indicative of the degree of alteration to the composition grassland vegetation types generally on the plains, and their status as probably the most threatened of Australia's major temperate ecosystems (Jones 1998). There is clear evidence for establishment of introduced species of *Plantago* in almost all records, suggesting that direct competition may have played a big part in the loss of the native species.

Alteration of dry land vegetation appears also to have impacted on the aquatic environments of individual sites. At both Tower Hill sites and Turangmoroke there are marked increases in Chenopodiaceae, indicating increasing salinity levels that are most probably linked to clearing induced salinisation. At Tower Hill, total deforestation of the

volcanic structure would have had a major influence, as would the damming of the outlet of the lake. In almost all records, sediment accumulation rates appear high compared to average rates for the Holocene as a whole and this suggests that disturbance has resulted in substantial erosion of catchment sediments and their deposition within the basins. However, Dodson et al. (1994) attributed the dramatic increase at Cobricio Crater to lower consolidation of recent sediments. This may be the case at this site, where the lake is surrounded by vegetated peat capable of trapping eroded material, but in lakes lacking marginal swamp there is evidence that material has eroded into the basins. At Keilambete, for instance, previously accumulated sediment along the lake margins has been washed into the basin as a result of a substantial fall in water level over the last century (Jones et al. 1998). The eroded material may be indistinguishable from freshly depositing lake mud. Of concern here is that pollen contained within the old sediments may be being redeposited and contaminating and distorting the pollen signature for the most recent time of European occupation.

It has been hypothesised by Crowley (1994b), from examination of a number of pollen records from southeastern Australia, that salinization, indicated by regional increases in Chenopodiaceae, was a major contributing factor to the substantial decline in salt intolerant Casuarinaceae. However, although there is good evidence for such a relationship between the two events at a few sites, salinity does not appear to have been a contributing factor at many other sites.

The impact of Europeans on the landscape has significantly influenced dissimilarity measures. Appropriately, squared chord distances have increased suggesting the creation of a landscape that has no close analogue in the pre-European vegetation. In line with this alteration, precipitation estimates become erratic with some records indicating highest or lowest values for the Holocene and one record (Bullenmerri) indicating both. The results are meaningless and provide graphic support for the decision to use pre-European rather than modern pollen spectra for quantitative palaeoclimatic reconstruction.

## CONCLUSIONS

There has been marked temporal and spatial variation in the vegetation of the Western Plains over the last 20,000 years or so, but much of this variation is contained within the latter part of the Pleistocene

and early Holocene. The plains were probably almost treeless during the Last Glacial Maximum, which extended to about 15,000 years ago. Most woody taxa would have been of shrub rather than tree form although *Callitris* may have been a more important component of the regional vegetation than it is today. The predominant vegetation type is inferred to have been steppe grassland dominated by Poaceae and Asteraceae that varied in composition across the plains. The lack of modern analogues in southeastern Australia inhibits more exact determination of the structure and composition of this vegetation. Calculated rainfall values suggest that mean annual rainfall was about 100–200 mm lower than that of today although estimates may be influenced by globally lower temperatures during this glacial period as well as statistical uncertainties. Neither mean temperature nor precipitation lowering would have led to the exclusion of trees and other factors such as incursions of cold polar air, globally lower carbon dioxide levels in the atmosphere, and altered seasonal distribution of rainfall, may also have been important influences.

During the late glacial period (15,000 to 10,000 years ago) available evidence suggests a further decline in woody plant representation, despite rising temperatures globally. The major influence appears to have been a reduction in effective moisture, most likely a result of rising temperatures, with expansion of saline environments and lunette formation. Maximum 'aridity' occurred between about 14,000 – 12,000 years BP. After this time there are suggested increases in both temperature, indicated by a reduction in the Asteraceae/Poaceae ratio that likely represents a switch from steppe-grassland to grassland, and rainfall, indicated by reductions in Chenopodiaceae, the beginning of sediment accumulation at many sites, cessation of lunette formation and expansion in the distribution of trees, largely *Allocasuarina verticillata*. Marked regional variation is indicated by much higher representation of *A. verticillata* values in sites within the Warrnambool area and later in the north of the plains than in the Camperdown-Colac area suggesting either eastern and northeastern expansion from glacial refuges off the basalt or more seasonal Mediterranean climatic conditions in the western and northern areas.

By the beginning of the Holocene (10,000 years ago), the tree cover over much of the Western Plains had virtually achieved present day levels, although there may have been a delay of about 1000 years in the north. Community composition continued to

change in the early Holocene with increased diversity of woody plants and, around 8000–7000 years BP, a sustained increase in *Eucalyptus* relative to Casuarinaceae except in the southeastern area where *Eucalyptus* had been the predominant taxon since at least the beginning of the Holocene. These changes are explained by a continued rise in rainfall combined with the establishment of a less seasonal climate, especially in the west and north. Despite lake level evidence for substantial subsequent changes in climate, including a maximum in effective precipitation between about 7500 and 5500 years BP, there has been little vegetation response and consequently little variation in constructed palaeoclimatic estimates. The sensitivity of the small Northwest Crater basin may be registering variation related to increased ENSO activity within the last 5000 years.

In contrast to the relative stability of the vegetation through much of the Holocene, marked changes are evident after European settlement with tree removal and planting and establishment of agriculture. Sites reveal a great deal of regional variation in impact but most common features are an early decline in Casuarinaceae, presumably due to alteration of the fire regime and selective cutting for firewood, a subsequent decline in *Eucalyptus* combined with an increase in Poaceae with major land clearance, and a severe decline in native *Plantago* and its replacement with exotic *Plantago* species. This latter change is probably a good indicator of the massive alteration to grassland habitats on the plains that is otherwise invisible because of the difficulty in separating native from introduced members of the dominant families Poaceae and Asteraceae on pollen morphological grounds, and the lack of pollen representation of most other herbaceous taxa. More local impacts included abrupt rises in Chenopodiaceae around some sites indicating a rise in salinity levels and increased erosion of sediments into lake basins.

The regional picture presented here does not totally support the idea that the vegetation of the basalt is largely insensitive to climate change (see Jones 1998, Dodson 2002). There appears to have been significant vegetation response to climate on a glacial-interglacial timescale although the limited variation in pollen representation around Bullenmerri suggests relatively minor vegetation change within at least some parts of the plains. It is certainly true that, in almost all records, there has been little change in vegetation through much of the Holocene despite evidence for significant variation in lake levels. Here, it is probably appropriate to consider factors such as

the heavy texture of the soils and perhaps frequent burning by Indigenous people as factors limiting tree growth. However, the proposed changes in the precipitation/evaporation ratio that have a critical influence on lake levels under the precipitation regime experienced over the plains would not necessarily be expected to have a major impact on vegetation composition. A proposed Holocene range of 450 mm (Jones 1998) would still place the region consistently under a dry sclerophyll forest/woodland cover dominated by essentially the same species. Furthermore, the proposal of soil as a limiting factor to vegetation development is not supported by the extended record from the Terang area, that clearly shows much greater variation during previous glacial /interglacial cycles and greater forest development during some inferred interglacial periods (Kershaw, D'Costa, Tibby et al. 2004). Similarly, there is no consistent inverse relationship between Casuarinaceae and Chenopodiaceae to support the proposition (Crowley 1994a, 1994b) that soil salinity has impacted severely on casuarina populations during the Holocene from the data presented here or through the late Quaternary period (Kershaw, D'Costa, Tibby et al. 2004; Harle et al. 2004) although waterlogging may have had an influence on the Casuarinaceae (Crowley 1994a). In relation to the question of Aboriginal burning, it is possible that alteration of fire regimes since the time of arrival of people, perhaps 45,000 years ago, may have had some impact on vegetation development during the Holocene (see Harle et al. 2004).

The use of analogue methodology for reconstructing past rainfall has been of some benefit although actual quantitative values have to be treated with some caution. In most records the standard error is greater than the range of RANN so that it is the trends in precipitation that are most useful. Precipitation estimates for the last glacial period seem realistic, despite the lack of close recent vegetation analogues from which estimates were derived, but the method failed to reflect dry conditions during the late glacial period. Analogue matching has, however, contributed to the consideration that a temperature increase, as much as a precipitation decline, was a contributing factor. The lack of notable rainfall trends within the Holocene is consistent with visual interpretation of the data, while the suggestion of slightly drier climates in the Pleistocene/Holocene transition and early Holocene in most diagrams exhibiting high Casuarinaceae percentages reinforced interpretation from visual interpretation. The data were not sufficiently refined to allow assessment of the significance

of fluctuations in most rainfall curves although high variability in the last 5000 years at Northwest Crater may be indicative of vegetation response to increase ENSO activity. High analogue distances in those spectra deposited within the period of European occupation generally indicate that the present vegetation landscape is very different to any experienced previously within the Holocene period. There is greater potential for more refined and accurate reconstructions with a denser network of recent pollen spectra, better chronological control on fossil sequences, and perhaps consideration of pollen taxa additional to the selected, common taxa considered in this review.

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